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# Mining Deep Ocean Manganese Nodules

## Description and Economic Analysis of a Potential Venture

By C. Thomas Hillman and Burton B. Gosling

UNITED STATES DEPARTMENT OF THE INTERIOR

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**UNITED STATES DEPARTMENT OF THE INTERIOR**
Donald Paul Hodel, Secretary

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Robert C. Horton, Director

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

| | | | |
|---|---|---|---|
| cm | centimeter | m | meter |
| cm/s | centimeter per second | $m^2$ | square meter |
| °C | degree Celsius | mm | millimeter |
| dwt | deadweight long ton | m/s | meter per second |
| d/yr | day per year | nmi | nautical mile |
| $g/cm^3$ | gram per cubic centimeter | pct | percent |
| ha | hectare | t | metric ton |
| h/d | hour per day | $t/km^2$ | metric ton per square kilometer |
| $kg/m^2$ | kilogram per square meter | t/yr | metric ton per year |
| km | kilometer | wt pct | weight percent |
| $km^2$ | square kilometer | yr | year |
| Lt | long ton | | |

# MINING DEEP OCEAN MANGANESE NODULES

## Description and Economic Analysis of a Potential Venture

By C. Thomas Hillman[1] and Burton B. Gosling[1]

ABSTRACT

This Bureau of Mines report describes an investigation of factors influencing economic viability of a proposed system to mine and process manganese nodules. The system consists of hydraulic dredging and ammonia leach processing designed to recover three metals: nickel, copper, and cobalt. A ferromanganese recovery plant is a considered option. Annual capacity is 3 million dry metric tons (t) nodules.

Aftertax rates of return (ROR's) of only 7.38 and 6.63 pct are predicted for three- and four-metal base scenarios, respectively. Sensitivity analyses indicate that variations in commodity prices, metal recoveries, and deposit grades produce similar incremental changes in ROR. Estimated cumulative effects of price variations are greatest. While three-metal operations generally yield higher predicted returns, potential increases in manganese price and process recovery could make four-metal operations most profitable.

Maximum variations in both capital costs and three-metal operating costs result in ROR changes of about 25 pct. In contrast, four-metal ROR's exhibit variations to 70 pct. Even so only a best case analysis, utilizing favorable variations in all categories tested, generated ROR's approaching a level thought necessary to trigger company interest. Consequently, it is concluded that nodule mining will not take place in the foreseeable future without significant financial incentives.

[1]Supervisory physical scientist, Western Field Operations Center, Bureau of Mines, Spokane, WA.

## INTRODUCTION

Deep ocean manganese nodules represent an exceptionally large and potentially important mineral resource. Deposits of the highest grade and abundance occur in the northeast equatorial Pacific Ocean in an area of about 10 million $km^2$. This area is of primary commercial interest and is known as the high-grade zone.

Manganese nodules are also called polymetallic nodules because they consist primarily of manganese and iron oxides that contain elevated concentrations of nickel, copper, and cobalt. Significantly, the United States is heavily dependent on foreign sources for all nickel, cobalt, and manganese. Therefore, it is in the Nation's best interest that these ocean resources be evaluated and integrated systems to mine and process them be proposed.

In response to this need, the Bureau is involved in a continuing Minerals Availability Program (MAP) effort to collect and analyze information on mineral resources and mining and processing systems. Data have been gathered during the past 7 yr through grants to Scripps Institution of Oceanography and Washington State University and by contacts with the U.S. Geological Survey, the National Oceanic and Atmospheric Administration (NOAA), and private consultants. Much raw data came from project DOMES (Deep Ocean Mining Environmental Study) sponsored by NOAA. DOMES involved a detailed investigation of the marine environment at three potential minesites (designated Sites A, B, and C) in the high-grade zone and a determination of possible environmental effects of manganese nodule mining. Figure 1 shows the high-grade zone and the three DOMES sites.

Several Bureau reports have resulted from the MAP effort. The latest report (1),[2] contains estimates of manganese nodule resources in the vicinity of the three DOMES areas and describes a proposed integrated system to mine, transport, and process nodules from one potential minesite in each of the three areas. Cost estimates were made and discounted-cash-flow analyses were performed to evaluate potential profitability. Results indicated an ROR of 6 pct or less after taxes, a figure that is only a small fraction of the estimated 25 to 30 pct ROR needed to attract risk capital. Because of these low predicted returns, the present study attempts to identify those factors having the most significant effects on the economics of proposed recovery systems discussed in reference 1. The goal is to provide information to both government and industry with information that will be used to more accurately plan for the eventual mining and utilization of manganese nodules.

This report first describes resources of a potential minesite (Subarea CI in reference 1), one of several previously evaluated. The area encompasses DOMES Site C and for this report is designated study area CI. All costing and subsequent analyses are based on resource estimates for this area. Because of high grade and abundance, nodule resources there are believed representative of deposits that will be mined and processed before any others; the term frequently used for such a deposit is "first-generation minesite." Following resource definition, an integrated recovery system is described, and costs for the system are estimated and summarized. A cost sensitivity analysis using multiple runs of the Bureau's MINISIM08 computer program (2) is subsequently described along with results and conclusions.

In context of publicly available information, it is believed that this analysis, based on resource estimates for actual deposits, should improve upon other financial analyses based on hypothetical resources. It is also reasonable to expect mining consortia to delineate and

[2]Underlined numbers in parentheses refer to items in the list of references preceding the appendix.


FIGURE 1. - Location of the northeast Pacific high-grade zone and DOMES Sites A, B, and C.

mine those areas within potential mine-sites of highest grade and abundance, thus potentially exeeding economic predictions in this study.

## RESOURCES

### LOCATION AND GEOGRAPHY

Study area CI is in the north-central portion of the Pacific high-grade zone, approximately 2,200 km southest of Los Angeles, CA (fig. 2). The area is approximately 57,600 km$^2$ and lies between latitudes 14.0° to 16.2° N and longitudes 124.8° to 127.0° W, at an average water depth of approximately 4,600 m.

Climate is moderate throughout the year; rainfall is slight and air temperatures average about 25° C for the entire year. Tropical storms and typhoons occur primarily during the summer months and usually last a day or two. An average of 15 storms per year occurred during the 1966-75 period, and an average of 11 of those occurred in the months of July through September.

Measurements made in 1975-76 by NOAA indicate surface currents are moderate, averaging about 17 cm/s (3). These currents flow in a west-southwest direction, and are controlled by moderate trade winds that blow steadily throughout the year. Surface currents gradually decrease to zero at a depth of 160 m; at that approximate depth currents reverse direction and flow eastward at low velocity. Although bottom current data for study area CI are unavailable, theoretical studies and water mass characteristics indicate a net eastward flow at low velocities (3).

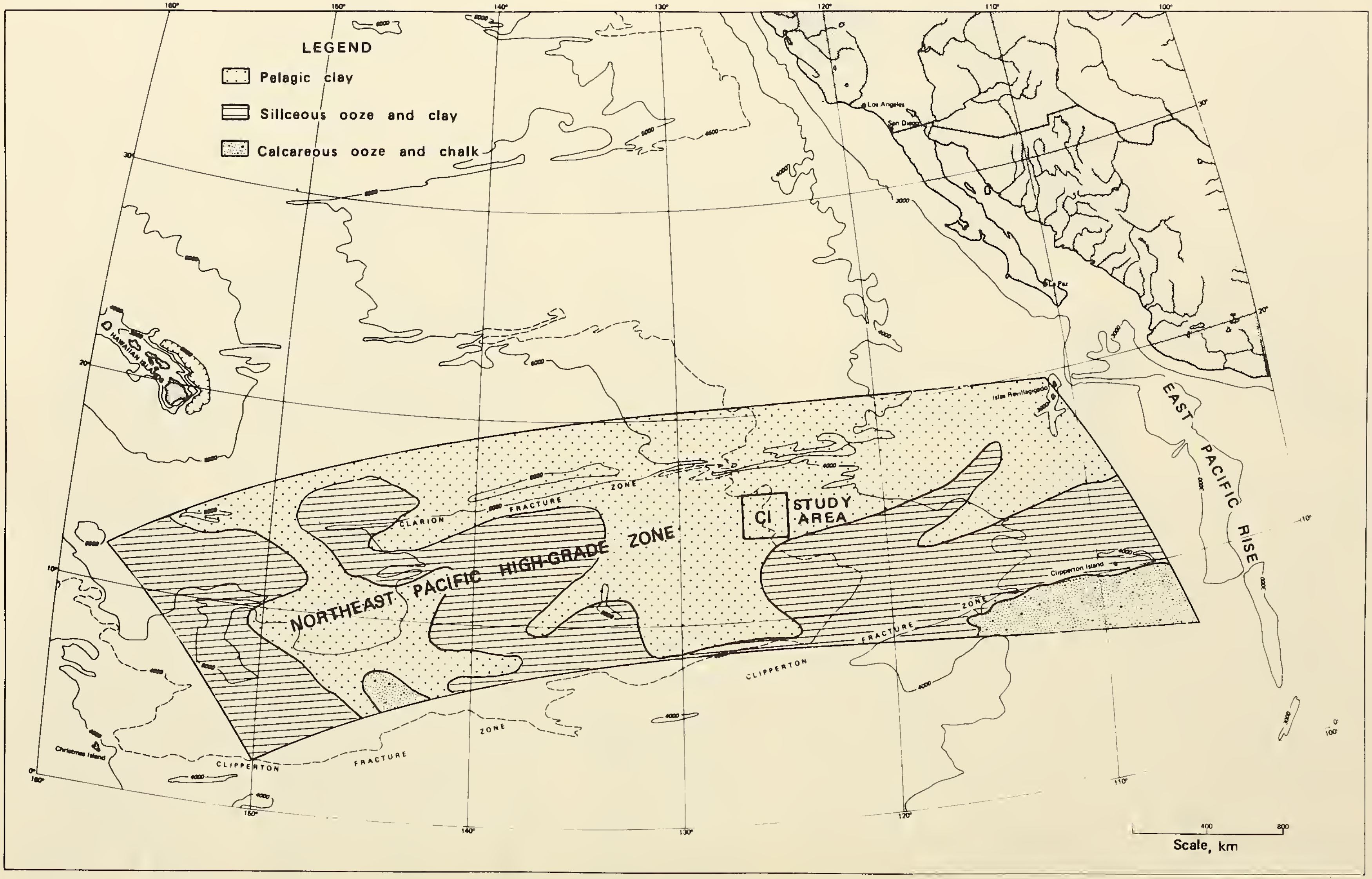


FIGURE 2. - Location of study area CI and sediment distribution in the northeast Pacific high-grade zone.

Based on known data, it is assumed that neither surface nor bottom currents would significantly hinder mining in study area CI. Tropical storms can be expected to preclude mining for 30 to 40 days annually, mostly during the summer months.

## GEOLOGIC SETTING

Essentially all of the high-grade zone, including study area CI, occurs within the Eastern Pacific Sedimentary Basin, which extends from about 5° to 20° N latitude and eastward from 170° W longitude and is bounded both east and west by seamount provinces. Sediment-covered hills dominate the ocean floor topography and are characteristically elongated and parallel (4), they trend north-south or northeast-southwest, and have slopes typically between 2° and 3° (5). Local relief is generally low, except in areas of current scour or fault scarps. Parallel scarps impart a stairstep effect on hillsides, and where accompanied by sediment slumping, underlying basalt bedrock is exposed.

Water depths decrease toward the East Pacific Rise (fig. 2), where oceanic crust is being formed within a narrow zone called a rift or spreading center. Progressive outward movement of newly formed crust results in successively older rocks in a westerly direction (6). Bedrock age in the area is mostly Oligocene, while further west crust is as old as Late Cretaceous.

Ocean floor in the area is covered by a reddish-brown to chocolate-colored pelagic clay unit. This unit contains as much as 65 pct illite, kaolinite, and smectite; the remainder consists mostly of siliceous organic material, primarily radiolaria, diatoms, silicoflagellate skeletal remains, and sponge spicules. Locally, calcareous material comprises as much as 5 pct of the sediment, but for the most part is dissolved before it reaches the seafloor. Elsewhere in the high-grade zone, pelagic clay grades into siliceous ooze and clay that contains variable yet high percentages of siliceous organic material. Calcareous sediments occur in the southeast and southwest parts of the zone (fig. 2). In study area CI, average bulk density of sediments is estimated to be about 1.3 g/cm$^3$ (3). Estimated sediment thickness is 100 m, and present day sedimentation rates probably range from 1 to 3 mm/1,000 yr (6). Rates may have been greater in the past to account for the 100-m accumulation during the past 30 million yr (middle Oligocene).

## DEPOSIT DESCRIPTION

Manganese nodule deposits occur as irregular, single-layer fields at the sediment-water interface. Typically, few nodules occur below a sediment depth of 1 m, and those within a meter of the ocean floor comprise an amount equal to about 25 pct of those at the sediment surface (6). Populations, defined as percentage of seafloor covered by nodules, range from zero to nearly 100 pct.

Individual nodules have a dull luster and are earthy brown to bluish black color. Shapes of smaller nodules are mostly spheroidal, with progressively larger ones becoming ellipsoidal and then discoidal. This phenomenon is attributed to unequal growth rates; bottom portions, nested in sediment, are thought to accrete more rapidly than exposed tops (7). Irregular shapes are common and result from either natural agglomeration of small nodules or the tendency of nodules to reflect morphology of irregularly shaped nuclei.

Surface textures range from smooth to very rough and may be attributed to differential growth patterns of constituent oxide phases. Porosity and internal surface area are both high, typically 50 pct and 200 to 300 m$^2$, respectively (8). Consequently, individual nodules contain about 30 wt pct moisture. Wet specific gravity is generally between 2.0 and 2.5.

Internally, nodules are composed of one or more nuclei surrounded by discontinuous, concentric layers of manganese and iron oxides. Nuclei may be shark teeth, whale ear bones, small pieces of other

nodules, or small rock fragments. Clay layers, generally present at irregular intervals between oxide layers, are thought to indicate long periods of non-growth. Concentric and radial fractures are nearly universal in larger nodules.

Nickel and copper probably occur within the manganese oxide minerals todorokite and birnessite by means of adsorption, lattice substitution, or ion exhange (8). The occurrence of cobalt is less well known, but relatively recent work (9) indicates that cobalt in low-grade nodules is contained principally in iron oxide phases. In high-grade nodules, manganese phases are preferentially enriched in cobalt.

## TONNAGE AND GRADE ESTIMATES

Quantity and grade estimates are based on information in reference 1. Evaluation of chemical analyses of samples from study area CI (10) show that the arithmetic mean of metal concentrations can be predicted within ±10 pct at a confidence level of 90 pct. Work by other investigators (11) using many hundreds of samples likewise indicates that grades within large areas of the high-grade zone can be predicted with similar accuracy.

Nodule abundances (weight per unit area of seafloor) and nodule tonnages calculated from those abundances are more difficult to determine. Even though deposits cover very large areas, local nodule populations are extremely variable. Over distances of a few meters, abundances typically range from near zero to 10 to 15 $kg/m^2$. Ideally, sampling should be conducted on a grid with coverage by television and seafloor photography between points. Because the purpose of most investigations to date has been research rather than resource evaluation, sampling locations are generally random and photographic coverage is along linear tracks. However, tonnage estimates are believed to be conservative, because photographic correction factors (12) that generally raise abundance-tonnage estimates could not be applied. These factors, used by mining consortia, require detailed data not publicly available.

Boundaries of the area are primarily based on locations of available sample data. A rectangular shape is used for convenience and does not necessarily delimit or enclose any single deposit. In reality, study area CI may include all or parts of several deposits separated by barren seafloor.

Table 1 contains mean metal concentrations (grade) calculated from assays of available samples taken at 64 sample sites in the study area. Combined concentrations of nickel plus copper (2.37 wt pct) is slightly greater than the 2.3 wt pct regarded by some (13) to be the mininum requirement for a viable minesite.

TABLE 1. - Mean metal content, study area CI

| | wt pct |
|---|---|
| Cobalt | 0.26 |
| Copper | 1.04 |
| Iron | 6.90 |
| Manganese | 26.80 |
| Molybdenum | .07 |
| Nickel | 1.33 |

Average abundance was calculated from estimates for individual ship stations. Estimates determined by sampling are not differentiated from those determined from photographs, nor is any greater significance attached to them. Assuming 30 pct water content, the calculated average of 11.7 wet $kg/m^2$ converts to 8.2 dry $kg/m^2$ or 8,200 dry $t/km^2$.

Gross dry tonnage can be easily figured by multiplying area size in square kilometers by the average dry abundance; in the case of study area CI, 57,600 $km^2$ times 8,200 dry $t/km^2$. However, the result can be misleading, because several practical considerations significantly lessen the amount of resource that can actually be recovered. Localized topographic features such as fault scarps and steep slopes reduce the minable area

to an estimated 75 pct of the minesite (14). Possibly one-third of the remaining area contains deposits with combinations of grade and abundance insufficient to warrant mining. As a result, it is reasonable to assume about half of the original site can be mined. Additionally, retrieval efficiencies of presently envisioned mine systems are expected to be about 90 pct. Also, ship maneuvering limitations indicate that only about 70 pct of the minable area will be traversed, resulting in a net mining efficiency of slightly more than 60 pct. Therefore, recoverable resources from first-generation mining may be only about 30 pct of the in situ tonnage.

Minable and recoverable resources are listed in table 2, as well as average nodule abundance, mine size, and other pertinent data. Proposed mining-transportation-beneficiation systems, costs, and economic analysis in succeeding sections are based on this information, and on the mean metal content in table 1.

TABLE 2. - Resource estimates and supporting data, study area CI

| | |
|---|---|
| Total area..................$km^2$.. | 57,600 |
| Minable area[1]...............$km^2$.. | 28,800 |
| Average abundance......dry $t/km^2$.. | 8,200 |
| Minable resource.......$10^6$ dry t.. | 236.2 |
| Minable nodules traversed....pct.. | 70 |
| Pickup efficiency............pct.. | 90 |
| Mining efficiency[2]..........pct.. | 63 |
| Recoverable resource[3]..$10^6$ dry t.. | 148.8 |

[1]50 pct of total area.
[2]Percent of nodules traversed times pickup efficiency.
[3]Minable resource times mining efficiency.

# INTEGRATED RECOVERY SYSTEM AND COSTS

## SYSTEM DESCRIPTION

The system proposed to recover nodules from study area CI is hypothetical because there is presently little commercial experience from which to draw. However, the system and costs are based on information from many knowledgeable sources, published and unpublished. Hydraulic mining and ammonia leach (Cuprion) processing are proposed because hydraulic mining systems have been tested somewhat successfully by both International Nickel Co. (INCO) and Deepsea Ventures, and Kennecott has apparently demonstrated in a pilot plant the feasibility of the ammonia leach process. Slurry transfer is the most probable method of transportation of nodule ore because the material is amenable, and considerable slurry handling experience exists in the minerals industry. For detail beyond what is given in the following discussion, the reader is referred to reference 1.

Prior to mining, the explored minesite would be characterized in detail. Large-scale maps would be drawn showing locations of all bottom obstructions and specific mining blocks with detailed grade and abundance information. Mining plans would be drawn up at least a year in advance and would consider not only economics, but also licensing requirements and other regulatory and environmental factors.

Mining is scheduled 20 h/d, 300 d/yr, with a projected annual production of 3.0 million dry t. Equipment modification and repair, drydocking, and other nonmining activity would take place during August and parts of July and September, when most major storms occur. Two ships, each towing hydraulic collectors at a velocity of 1.0 m/s, would conduct operations independently of one another. Nodules would be dislodged, screened, and channeled to a large-diameter pipe connected to the ship. Submerged hydraulic pumps would maintain upward flow of a slurry composed of water, nodules, and nodule fragments.

Aboard the ship, nodules would be screened, conveyed to storage, and dewatered by decantation. To prevent

formation of a surface plume, decanted sediment and biogenic debris would be discharged through a pipe extending to a depth of about 200 m (15). No attempt to upgrade the ore is presently envisioned because it is not amenable to conventional flotation or other cost-effective means; the metals of interest are intimately associated with the oxide matrix.

Every few days nodules would be reslurried and pumped through a flexible pipe to 70,000-dwt-capacity nodule transports where they would be dewatered and transported to a terminal on the west coast of the United States. At the terminal, portable units would reslurry and pump the ore to holding ponds on shore. From there the nodule slurry would be pumped an assumed distance of 40 km inland to the processing plant. Table 3 is a summary of pertinent transportation data. Three transport vessels, each making 23 trips annually, would be required to support a 3.0-million-t-capacity plant.

TABLE 3. - Transportation data summary, study area CI

| | |
|---|---|
| Transport capacity, t: | |
| Wet ore[1] | 64,000 |
| Dry ore | 44,800 |
| Distance to port...nmi.. | 1,840 |
| Cycle time...days.. | 13 |
| Annual trips per vessel | 23 |
| Number of vessels required | 3 |

[1]90 pct of the nominal capacity of 70,000 Lt.

Operations at the Cuprion plant would be conducted 24 h/d, 330 d/yr, at full capacity. The wet ore would be reclaimed from storage, and ground in a mixture of seawater and recycled process liquor containing dissolved copper and ammonium carbonate. Cuprous ions, generated by introduction of carbon monoxide in a series of reaction vessels, catalyze the reduction of manganese from the tetravalent to the divalent state, thereby releasing metals bound in the oxide matrix. The metals are separated from the solid residue by countercurrent washing, and the residue is processed with steam to recover ammonia and carbon dioxide. Nickel and copper would be extracted from solution by liquid ion exchange followed by electrowinning on high-purity cathodes. Cobalt would be chemically precipitated, purified, and recovered as metallic or oxide powder.

A facility to recover manganese in the form of ferromanganese is a considered option. Carbonate residue from the ammonia recovery section of the Cuprion plant would be washed and centrifuged (16). Prior to flotation with saponified fatty acids, thickened residue would be mixed with fresh water, soda ash, caustic soda, and sodium silicate. Manganese carbonate would be recovered in the froth as a concentrate assaying up to 40 pct manganese. The concentrate would be thickened to 50 pct solids, and then dried and calcined in a rotary kiln to make synthetic manganese oxide. This material would be stored or conveyed directly to submerged resistance furnaces charged with limestone, silica flux, coke, and iron ore. Slag would be skimmed off for disposal, and molten ferromanganese (78 pct Mn) poured into molds for cooling and shipment. The ferromanganese plant would operate 330 d/yr, and process an estimated 3 million t of Cuprion residue annually.

Tailings from both Cuprion and ferromanganese plants would be combined with other plant wastes and pumped as far as 100 km to a disposal site. At the disposal site, the tailings would be pumped into conventional waste impoundments. Granulated slag hauled from the ferromanganese plant would be a secondary source of bank material, if needed. Successive ponds would be stabilized in various ways in accordance with appropriate environmental regulations.

## SYSTEM COSTS

All cost estimates in this study are in January 1983 dollars. Most are updated from January 1981 costs presented in reference 1. The time and tonnage basis for working capital calculations is changed, resulting in slight increases in mine and transportation working capital

and a small decrease in processing capital. Also, plant capital has been reduced to reflect recent estimates (17). Indexing data used are from a Bureau cost index computer program and price indices published by the Bureau of Labor Statistics.

Tables 4 and 5 are summaries of capital and operating costs for the proposed integrated recovery system. Tables A-1 through A-3 of the appendix contain additional cost detail and descriptions of the various cost factors.

TABLE 4. - Capital cost summary, million January 1983 dollars

| | Investment |
|---|---|
| Mining...................... | $590.6 |
| Transportation and transfer.. | 310.6 |
| Cuprion plant and facilities. | 726.9 |
| Total (3-metal)......... | 1,628.1 |
| Ferromanganese plant......... | 215.3 |
| Total (4-metal)......... | 1,843.4 |

TABLE 5. - Operating cost summary, January 1983 dollars

| | Annual $10^6$ | Per dry t ore |
|---|---|---|
| Mining.................. | $76.5 | $25.50 |
| Transporation and transfer................ | 36.7 | 12.23 |
| Cuprion plant and facilities.............. | 110.9 | 36.97 |
| Total (3-metal)..... | 224.1 | 74.70 |
| Ferromanganese plant..... | 216.6 | 72.20 |
| Total (4-metal)..... | 440.7 | 146.90 |

Mine capital includes money for 6 yr of exploration and detailed site characterization; once mining begins this expense is treated as an operating cost. The research and development budget of nearly $158 million is divided about evenly between mining and processing. Working capital is based on full production for 15, 12, and 6 months, respectively, for mining, transportation, and processing. Additional capital of $23.2 million is allowed for exceptional expenses associated with at-sea testing and modifying of the collector. Mine ships, on-board equipment, pipelines, and collectors are assumed to be new and constructed in the United States.

Transportation investments include purchase of three new European-built ships for slightly more than $200 million. Also included are costs for construction of an offloading facility (slurry terminal) on a 10-ha site, 40 km of slurry pipeline to the plant, and purchase of a high-speed supply boat.

Processing capital consists of all land purchases, equipment, buildings, a 100-km slurry line to tailing disposal, an 8-km railroad spur line, an 8-km access road, and installation of turbines for generation of power for Cuprion plant operation. Power for a ferromanganese plant would be purchased. Not included is capital for infrastructure such as townsite.

Operating costs include allowances for wages and benefits, material and supplies, maintenance and repair, fuels and utilities, and insurance. Subsistence for ship's crew is included in mining and transportation, while costs associated with operation of a small supply boat, unloading facility, and pipeline (40 km) to plant are charged to transportation. Extraordinary expenses associated with processing include maintenance of the railroad spur and operation of the 100-km pipeline to waste disposal. Operation of a ferromanganese plant at full capacity incurs the largest single operating expense, nearly $120 million for purchased power.

## ECONOMIC ANALYSIS

### DISCUSSION

Financial analyses carried out during the initial Bureau study of three potential minesites (1) resulted in low predicted ROR's. Two analyses for each site were reported; one for the Cuprion process, which recovers nickel, copper, and cobalt (three-metal), and one for Cuprion plus ferromanganese (four-metal)

recovered from processing about half of the carbonate residue available from Cuprion processing. Three-metal ROR's ranged from 4.1 to 6.0 pct, while four-metal projections ranged from 3.5 to 5.2 pct. Considering political and technical risks, these predictions are far below the 25 to 30 pct ROR that might attract venture capital.

This study attempts to identify through sensitivity analysis, those factors that most affect economic viability of the proposed nodule mining venture; factors that should be subjected to close scrutiny in future planning and evaluation. The sensitivity analysis addresses mining and processing of nodules from study area CI, an area representative of first-generation minesites, those having deposits of relatively high grade and abundance. The proposed integrated recovery system and associated costs serve as the basis for two scenarios or base cases: a three-metal and a four-metal operation. Several cost factors associated with these base cases are varied through a series of financial analyses using the Bureau of Mines MINSIM08 computer program (2). The factors are varied independently to determine effects on predicted ROR.

## BASE CASE DESCRIPTION

Both the three- and four-metal operations utilize descriptions and costs presented in preceding sections. The three-metal case is essentially the same as described in reference 1; costs are updated. However, the four-metal case involving the add-on ferromanganese plant is different. Instead of recovering ferromanganese from only half the Cuprion process residue, the entire amount is treated to produce substantially more metal. Subsequent financial analyses indicate that the larger production scheme would be slightly more profitable.

Figure 3 depicts the relatively aggressive project schedule assigned to both base cases. Project timing, tax treatment, and other assumptions are identical to one another. Research and development would begin as soon as possible in the first year and would continue through the seventh year. Exploration would also begin in the first year and continue through year 6, then resume in year 10 and be carried on through year 30. The exploration ship would assist in mining tests during years 7 through 9. Plant construction would last 4 yr (years 6 through 9) and ship construction about 5 yr. Keel for the first ship would be laid in year 6, with completion of construction in year 8. At-sea tests would be conducted late in year 8 and early year 9. A second ship would be constructed in years 8 through 10, and improvements made during testing of the first ship would be incorporated. Production would begin in the 10th year;

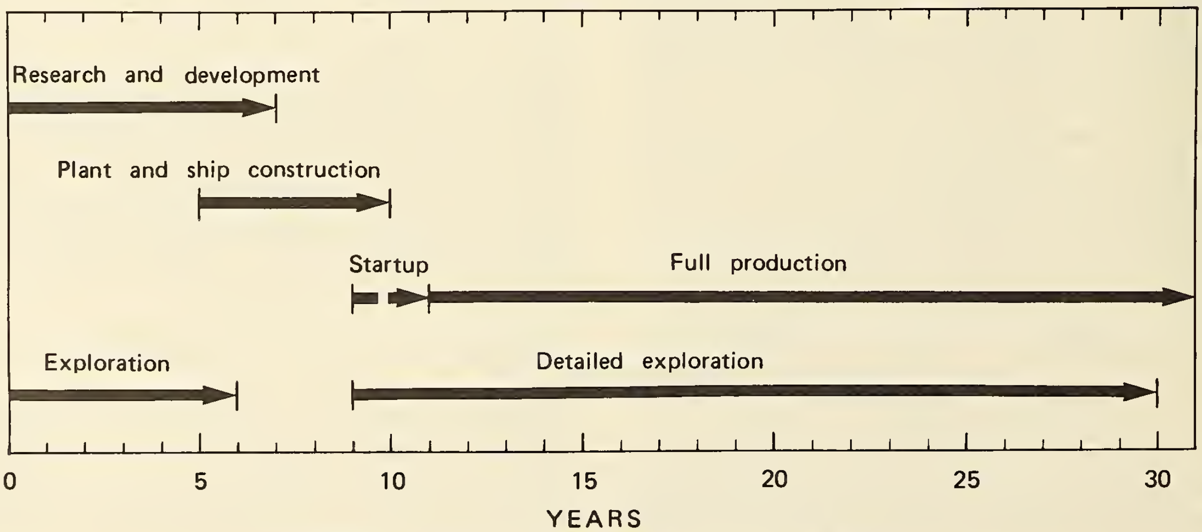


FIGURE 3. - Base case project development schedule.

full capacity of 3 million dry t annually is scheduled to begin in year 12 and continue for 20 yr.

Assumptions that materially affect results of the analysis include the following:

1. A go-ahead decision is made early enough to allow proper planning for construction.

2. Costs and commodity prices escalate at the same rate.

3. Equity capital is used, thus no finance charges are incurred.

4. A 9-pct State income tax and 4 pct property taxes are included as well as Federal income tax.

5. A payment of 0.75 pct excise tax on gross value is assumed, which is mandated by the Deep Seabed Hard Mineral Resource Act.

6. Depletion is used; 15 pct for copper and 22 pct for nickel, cobalt, and manganese.

Metal contents (grade), estimated recoveries, and commodity prices for the two base cases are listed in table 6. Commodity selling prices for nickel, copper, and ferromanganese represent a 10-yr mean (1973-82) calculated in constant 1983 dollars. The average cobalt price was adjusted downward, because mean yearly values for the 1978-81 period are considered artificially high. This was done by assigning the mean of the two enclosing years, that is 1977 and 1982, to the four high years in the computation.

## METHODOLOGY AND RESULTS

The primary tool used in the sensitivity analysis is the Bureau's mine simulation computer program (MINSIM08) devised by personnel of the Minerals Availability Field Office, Denver, CO (2). This program, among other things, computes the ROR for potential investments when required operational parameters are supplied. This is the profitability yardstick used for comparison of the various factors tested. Necessary data required by the program include capital and operating costs, investment scheduling, metal processing recoveries, ore grade, and various product characteristics.

TABLE 6. - Commodity data summary, base case conditions

| | Metal content, wt pct | Recovery, pct | Price per lb |
|---|---|---|---|
| Cobalt....... | 0.26 | 65 | $8.53 |
| Copper....... | 1.04 | 92 | 1.17 |
| Manganese[1]... | 26.80 | 44 | .25 |
| Nickel....... | 1.33 | 92 | 3.62 |

[1]Recovered as ferromanganese, containing 78 pct manganese; listed price is per pound ferromanganese.

The first step toward sensitivity analysis requires identification of parameters to be tested. Those chosen include capital costs, operating costs, ore grade, process recoveries, metal prices, and the length of the preproduction period. Additionally, best case runs were made to determine results of a combination of favorable factors on the two base cases.

Individual parameter ranges were established according to the uncertainty of the original estimate. For example, capital and operating costs were varied up to 25 pct, while ore grade variance was limited to ±10 pct. Once a range was assigned, analyses were completed using the extreme values of the range to demonstrate maximum effects of the parameter on ROR. Additional, intermediate runs were made for capital and operating cost parameters, because of the relatively large degree of uncertainty attached to costs.

Base case analyses were run initially, and results served as standards for all subsequent analyses. Resulting ROR's are, in percent,

- Three-metal (Cuprion)... 7.38
- Four-metal............. 6.64

These values are slightly higher than those in reference 1 because of minor differences in methodology and the change to full production of ferromanganese. The four-metal base case is slightly less profitable despite significant additional revenues, because of a near doubling of operating costs.

Table 7 contains estimated ROR's from a series of runs testing variations in metal recoveries. Logically, the greatest potential effect on return is exhibited by manganese, because there is a much greater potential for variance. Cobalt has the second greatest potential affect, resulting from a combination of high product value and relatively high variances. Incrementally, increased nickel recovery raises projected return the most; about 1.3 pct for every percent increase. Manganese raises the ROR about 1.0 pct for each percent rise in recovery. For cobalt and copper the incremental rise in ROR is 0.44 and 0.31 pct, respectively.

TABLE 7. - Metal recovery options and resultant rates of return, percent

| | Recovery | | | ROR | | |
|---|---|---|---|---|---|---|
| | Low | Base | High | Low | Base | High |
| Cobalt..... | 60 | 65 | 70 | 7.13 | 7.38 | 7.63 |
| Copper..... | 90 | 92 | 94 | 7.33 | 7.38 | 7.43 |
| Manganese[1]. | 35 | 44 | 60 | 4.93 | 6.64 | 9.08 |
| Nickel..... | 90 | 92 | 94 | 7.16 | 7.38 | 7.59 |

ROR Rate of return.

[1]Recovery from Cuprion manganese carbonate tailing.

Processing feed grade ranges were set at only ±10 pct, because considerable confidence can be placed in grade estimates. However, as the nickel, copper, and cobalt grades are assumed directly proportional to one another, it is also appropriate to demonstrate the effect of varying all three recovered metals simultaneously. Results of grade variation runs are listed in table 8. As might be expected, the ROR variation is a direct reflection of the relative level of contribution each metal makes in proportion to total revenues for the operation. Therefore, nickel has the greatest effect followed by cobalt and then copper. Although a much larger effect occurs when all three metals are varied simultaneously, the change in ROR is still not great enough to suggest that slight grade changes will significantly affect proposed operations.

TABLE 8. - Effects of grade variations on rates of return, percent

| | Low, -10 pct | Base | High, +10 pct |
|---|---|---|---|
| Cobalt................ | 7.00 | 7.38 | 7.75 |
| Copper................ | 7.14 | 7.38 | 7.61 |
| Nickel................ | 6.38 | 7.38 | 8.31 |
| 3-metal variation..... | 5.67 | 7.38 | 8.87 |

Similar analyses were not conducted for the manganese producing options, because expected grade variations are insignificant when compared to wide limits placed on manganese recovery.

The third parameter investigated was commodity price. Range end members were taken as the extreme upper and lower values for 1973-82 annual prices. In order to make direct comparisons, these values were escalated to constant 1983 dollars using price indexes published by the Bureau of Labor Statistics. Cobalt is the one exception; range was determined from the highest and lowest annual average excluding years 1978-81, because of the previously mentioned artifically high selling price during those years. Table 9 summarizes the various price options and ROR's resulting from MINSIM08 analysis.

From this analysis it is seen that nickel price variations have the largest incremental effect on ROR. For instance a 1-pct rise in nickel price translates to about a 1.25-pct change in ROR. Again, this fact is a direct reflection of the relative importance of nickel revenue. It is also estimated that manganese, cobalt, and copper would add 1.1, 0.41, and 0.33 pct, respectively, per 1 pct rise in commodity price.

TABLE 9. - Price options and resultant rates of return

| | Low | Base | High |
|---|---|---|---|
| Price per pound:[1] | | | |
| Cobalt......... | $6.75 | $8.53 | $13.00 |
| Copper......... | $0.77 | $1.17 | $1.57 |
| Manganese[2]..... | $0.186 | $0.250 | $0.358 |
| Nickel......... | $3.18 | $3.62 | $4.13 |
| ROR, pct: | | | |
| Cobalt......... | 6.69 | 7.38 | 8.98 |
| Copper......... | 6.50 | 7.38 | 8.20 |
| Manganese...... | 4.12 | 6.64 | 9.80 |
| Nickel......... | 6.11 | 7.38 | 8.71 |

ROR Rate of return.
[1]Escalated to 1983 dollars.
[2]Price per pound ferromanganese.

Capital and operating costs were analyzed next. Because of a relatively high uncertainty attached to estimates, end points were established at ±25 pct. Table 10 contains results of test runs including intermediate runs using ±10 pct. Although incremental effects were only slightly higher than factors previously discussed, the wide test ranges resulted in the greatest effects on ROR's of any of the four parameters tested. Significantly, variations in operating costs exerted much more influence on ROR than all other factors including capital costs. This is especially true of four-metal operations which included the only test run to exceed 10 pct return. However, the resultant ROR of about 11 pct is still far below reasonable expectations.

TABLE 10. - Effects of capital and operating cost variations on rates of return, percent

| Variation..... | +25 pct | +10 pct | Base | -10 pct | -25 pct |
|---|---|---|---|---|---|
| Capital: | | | | | |
| Cuprion..... | 6.08 | 6.70 | 7.38 | 8.14 | 9.21 |
| 4-metal..... | 5.31 | 5.99 | 6.64 | 7.36 | 8.28 |
| Operating: | | | | | |
| Cuprion..... | 4.96 | 6.15 | 7.38 | 8.21 | 9.39 |
| 4-metal..... | 2.18 | 5.49 | 6.64 | 9.02 | 11.17 |

It was considered possible that lengthy lead time results in such significant future cash flow discounting that variations of previous parameters achieves at best only modest increases in the ROR. To examine this possibility the preproduction period was shortened from 9 to 5 yr, maintaining investment category totals constant, but accelerating expenditure rate. In table 11, returns of the resultant compressed schedule are compared with base returns. Considering the original premise and the degree that the preproduction period is shortened, it is surprising that so little effect is noted.

TABLE 11. - Effects of shortened development schedule on rates of return, percent

| | Base | Shortened |
|---|---|---|
| Cuprion................ | 7.38 | 8.10 |
| 4-metal................ | 6.64 | 7.25 |

Two additional best case runs were made in an attempt to evaluate the cumulative effect of varying all test parameters simultaneously. Worst case scenarios were not run because they would produce extremely low or negative returns. In addition to using high values for recoveries, prices, and grades, the best case included 25 pct decreases in capital and operating costs, and a shortened development schedule discussed in the preceding paragraph. As shown in the following tabulation, there is a marked improvement in ROR's.

- Three-metal (Cuprion) 19.3 pct ROR
- Four-metal........... 23.7 pct ROR

Particularly interesting is the potential of four-metal operations to be slightly more profitable than three-metal. However, these predicted returns would still be of marginal interest to potential ocean miners.

Table 12 summarizes data pertaining to increased ROR's resulting from the most favorable options. Actual predicted returns are on the summary side of the table while figures on the right side (change) are percent increase, calculated by dividing the actual amount of increase by the base case ROR (either 7.38 or 6.64) and multiplying by 100. Unfavorable options are not summarized, because of extremely low returns which preclude

TABLE 12. - Rates of return effected by favorable options, percent

| | Summary[1] | | | Change (increase)[2] | | |
|---|---|---|---|---|---|---|
| | Metal recovery | Deposit grade | Commodity price | Metal recovery | Deposit grade | Commodity price |
| Cobalt........... | 7.63 | 7.75 | 8.98 | 3.4 | 5.0 | 21.7 |
| Copper........... | 7.43 | 7.61 | 8.20 | 0.6 | 3.1 | 11.1 |
| Nickel........... | 7.59 | 8.31 | 8.71 | 2.8 | 12.6 | 18.0 |
| Ferromanganese... | 9.08 | NAp | 9.80 | 36.7 | NAp | 47.6 |
| | Capital costs | Operating costs | Shortened development | Capital costs | Operating costs | Shortened development |
| 3-metal.......... | 9.21 | 9.39 | 8.10 | 24.8 | 27.2 | 9.8 |
| 4-metal.......... | 8.28 | 11.17 | 7.25 | 24.7 | 68.2 | 9.2 |

NAp Not applicable.

[1]Compare with base case--3-metal, 7.38 pct; 4-metal, 6.64 pct.

[2]Relative change, calculated by dividing the amount of increase by the base rate of return (ROR) and multiplying by 100.

any thought of mining. Differences in ROR's resulting from independent changes in metal recovery, grade, and price variations are a function of parameter range and revenue generated by the affected commodity. As an example, nickel contributes much more revenue to proposed operations, yet greater variance both in recovery and commodity price of cobalt accounts for larger potential increases in ROR. On the other hand, estimated grade variability for the two commodities is the same (10 pct), and the predicted ROR increase for nickel is two and one-half times that of cobalt.

Potential impacts related to copper are comparatively low, because of relatively low commodity value and low degree of variance. Conversely, changes in ferromanganese parameters substantially influence ROR's, both by contributing a large percentage of revenue and by having fairly high degrees of uncertainty associated with metal recovery and selling price.

Rates of return associated with relatively large variations of capital and especially operating costs are also most significant. Predicted ROR increases range from about 25 pct, for 25 pct less capital investment, to nearly 70 pct for a 25-pct reduction in four-metal operating expense. Shortened development period (9 to 5 yr) has little effect on ROR; but in the analysis costs were not reduced, only the rate spending was increased. A larger and possibly significant increase might result if the shortened development period was accompanied by less capital spending.

The best case scenarios yielded very large percentage increases in ROR's; approximately 160 and 260 pct for three- and four-metal operations, respectively. While predicted returns are respectable, they are dependent on a series of fortunate circumstances, not likely to occur simultaneously.

## SUMMARY AND CONCLUSIONS

The following statements summarize results of the sensitivity analyses described in preceding sections:

1. Incremental changes in metal recoveries, deposit grade, and commodity price affects ROR's, similarly. Accordingly, a 1-pct variance in grade has nearly the same effect on return as would a 1-pct change in price or recovery

2. Among deposit grade, metal recovery, and commodity price, the potential for changing ROR in relation to the base case is greatest for commodity price. This is because price estimates are less

reliable and consequently, test ranges were greater.

3. Comparisons of three- and four-metal operations indicate that under certain circumstances (i.e., high manganese recovery and commodity price) four-metal operations could be slightly more profitable. This is borne out in the best case scenarios.

4. Based on proposed integrated operations, changes in capital costs affect both three and four-metal operations about equally. For a 1-pct change in investment, there is about a 1-pct change in ROR.

5. Variation of operating costs affects four-metal operations dramatically, resulting in an estimated 2.7-pct change in ROR for every percentage change in operating expenses. Changes in three-metal ROR are about 1.1 to 1.

6. The sensitivity analysis shows that reasonable variations from the base case still result in ROR's well below the 25- to 30-pct thought to be required. Only the best case predictions approach that level.

Based on the foregoing analysis it is most likely that nodules will not be mined and processed in the foreseeable future without significant financial incentives. The incentives could be in the form of price supports, tax breaks, or other programs such as financing research and development.

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# APPENDIX.--CAPITAL AND OPERATING COST DETAIL FOR STUDY AREA CI

TABLE A-1. - Mine costs,[1] million January 1983 dollars

| | Costs | Description |
|---|---|---|
| | CAPITAL | |
| Fixed capital: | | |
| Exploration...................... | $21.0 | Initial 6-yr program. |
| Research and development......... | 75.3 | 7-yr program. |
| 2 mine ships..................... | 199.5 | Capacity: 1.5 million t/yr each. |
| 2 nodule collectors.............. | 7.5 | Approximate width, 10 m. |
| 3 pipelines...................... | 51.7 | 40-cm ID, including 1 spare. |
| 2 pumping systems................ | 29.7 | Pumps, connectors, valves. |
| 2 sets of on-board equipment..... | 87.1 | Nodule handling, storage. |
| Total........................ | 471.8 | |
| Startup costs...................... | 23.2 | Equipment testing, redesign. |
| Working capital.................... | 95.6 | Basis: 1.25 yr, 3.75 million dry t. |
| Total investment............ | 590.6 | |
| | OPERATING[2] | |
| Direct operating: | | |
| Wages and benefits............... | $21.3 | 4 crews, 2 per ship. |
| Subsistence and supplies......... | 2.0 | Food and miscellaneous supplies. |
| Maintenance and repair........... | 27.5 | Ship and equipment. |
| Insurance........................ | 6.0 | Ship, equipment, and personnel. |
| Fuel............................. | 9.2 | Approximately 51,000 t diesel. |
| Lubrication and oil.............. | 0.1 | Ship and equipment. |
| Exploration and continuing research and development. | 6.4 | Mine characteristics and equipment improvement. |
| Total........................ | 72.5 | |
| General and administrative......... | 4.0 | 5.5 pct of direct costs. |
| Annual operating cost......... | 76.5 | |

[1]Estimates for 2 complete mining systems.
[2]Total mining cost per dry metric ton of ore: $25.50.

TABLE A-2. - Transportation costs, million January 1983 dollars

| | Costs | Description |
|---|---|---|
| | CAPITAL | |
| Fixed capital: | | |
| 3 transports | $201.7 | Capacity: 44,800 dry t ore each. |
| Slurry terminal | 40.8 | Dock and all facilities, 10 ha. |
| Slurry pipeline | 20.7 | 40 km, includes land purchase. |
| Supply boat | 1.5 | High-speed shuttle. |
| Total | 264.7 | |
| Working capital | 45.9 | Basis: 1.0 yr, 3.0 million dry t. |
| Total investment | 310.6 | |
| | OPERATING[1] | |
| Direct operating: | | |
| Transport: | | |
| Wages and benefits | $4.7 | U.S. crews, 3 transports. |
| Subsistence and supplies | .5 | Food and miscellaneous supplies. |
| Maintenance and repair | 6.2 | Ships and equipment. |
| Insurance | 1.4 | Ships, equipment, and personnel. |
| Fuel, lubrication, oil | 8.9 | Approximately 49,400 t diesel. |
| Port charges | 1.0 | Docking, tieup, and miscellaneous. |
| Helicopter | .7 | Crew, fuel, maintenance, repair. |
| Total | 23.4 | |
| Supply boat | 1.8 | Do. |
| Total vessel costs | 25.2 | |
| Transport unload and store | 3.1 | Operation, maintenance, repair. |
| Slurry pipeline to plant | 6.5 | Do. |
| Total | 34.8 | |
| General and administrative | 1.9 | 5.5 pct of direct costs. |
| Annual operating cost | 36.7 | |

[1]Total cost per day metric ton of ore: $12.23.

TABLE A-3 - Process costs, million January 1983 dollars

| | Costs | Description |
|---|---|---|
| CAPITAL | | |
| CUPRION PLANT | | |
| Fixed capital: | | |
| Research and development..... | $82.5 | 7 yr, including pilot plant. |
| Land........................ | 2.6 | About 90 ha, including ferromanganese site. |
| Plant and equipment.......... | 370.3 | Installed cost plus auxiliaries. |
| Utilities and service........ | 159.1 | Installed cost. |
| Waste disposal............... | 30.3 | Land, piping, ponds. |
| Pipeline, waste disposal..... | 20.9 | 100 km, includes land purchase. |
| Railroad spur and road....... | 5.7 | 8 km each, includes land. |
| Total.................... | 671.4 | |
| Working capital................ | 55.5 | Basis: 0.5 yr, 1.5 million dry t. |
| Total investment.......... | 726.9 | |
| FERROMANGANESE PLANT | | |
| Fixed capital: | | |
| Plant and equipment.......... | 129.6 | Installed cost plus auxiliaries. |
| Utilities and service........ | 31.1 | Installed cost. |
| Total.................... | 160.7 | |
| Working capital................ | 54.6 | Basis: 0.5 yr, 0.7 million dry t. |
| Total investment.......... | 215.3 | |
| Grand total.............. | 942.2 | |
| OPERATING[1] | | |
| CUPRION PLANT | | |
| Direct operating: | | |
| Wages and benefits........... | $18.6 | Operators, maintenance, technical, professional, management. |
| Materials and supplies....... | 4.0 | Operating chemicals and reagents. |
| Utilities and fuel........... | 40.5 | Coal, power, petroleum, water. |
| Capital-related expenses..... | 31.8 | Fixed expenses: maintenance, materials, insurance. |
| Waste disposal............... | 7.8 | Operating new and existing ponds. |
| Pipeline to waste disposal... | 2.7 | Operating, repair, and maintenance. |
| Railroad spur and access road | 0.2 | Do. |
| Total.................... | 105.6 | |
| General and administrative..... | 5.3 | 5.0 pct of direct operating. |
| Annual operating cost..... | 110.9 | |
| FERROMANGANESE PLANT[2] | | |
| Direct operating: | | |
| Wages and benefits........... | 32.0 | Operators, maintenance, technical, professional, management. |
| Materials and supplies....... | 43.6 | Operating chemicals and reagents. |
| Utilities and fuel........... | 118.6 | Coal, power, petroleum, water. |
| Capital-related expenses..... | 12.1 | Fixed expenses: maintenance, materials, insurance. |
| Total.................... | 206.3 | |
| General and administrative..... | 10.3 | 5.0 pct of direct operating. |
| Annual operating cost..... | 216.6 | |
| Grand total.............. | 327.5 | |

[1]Total cost per dry metric ton of ore: $109.17--$36.97 (Cuprion) and $72.20 (ferromanganese).

[2]Includes flotation, calcining, smelting, and handling as well as shipment of the ferromanganese to east-coast markets.

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UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF MINES
4800 FORBES AVENUE
PITTSBURGH, PENNSYLVANIA 15213